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5G Technology and Spectrum

Technology & Innovation

24th of August 2015

Official FCC Blog: Leading towards Next Generation "5G" Mobile Services

Tom Wheeler, FCC Chairman, August 3, 2015

- *"In addition, as an implementation of existing flexible rules, I foresee lower-frequency bands playing a role in 5G. For example, the timing of the incentive auction makes the 600 MHz band a prime candidate for deployment of a wide-area 5G coverage layer. In much the same way that 700 MHz paved the way for America's world-leading deployment of 4G, so could 600 MHz accelerate U.S. deployment of 5G."*
- *"The spectrum bands proposed by the United States to be studied for consideration at WRC-19 include 27.5-29.5 GHz, 37-40.5 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, and 59.3-71 GHz. We will consider these bands, or a subset of the bands, in further detail in an upcoming NPRM, with the goal of maximum use of higher-frequency bands in the United States by a wide variety of providers. We are committed to working with both domestic and international partners on identifying spectrum and on conducting the necessary technical sharing and compatibility studies."*

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Executive Summary

- **5G needs both licensed and unlicensed spectrum just like 3G and 4G**
  - Traditional carrier grade business model has been licensed
  - Carrier grade unlicensed model, although attractive, remains unproven
  - Licensed spectrum creates greater certainty for investment
- **Bandwidths for licensed and unlicensed should be comparable**
  - 4G: WiFi is 20 MHz BW @ 5GHz, LTE is also 20 MHz
  - Evolutions of 4G: Carrier aggregation for both LTE and WiFi ~ 100 MHz
  - 5G: 802.11ad is 2.156 GHz BW
  - Licensed 5G should include 2 GHz BW
- **5G will provide an order of magnitude improvement in performance**
- **5G license band needs to large enough to support multiple operators**
  - Need common devices to support multiple operators for economies of scale
  - Licensed bands that are very far apart would need multiple radios to support the specific allocations
- **71-76 GHz and 81-86 GHz should remain under consideration**
  - Currently allocated worldwide for backhaul
  - Potential for common worldwide allocation improving economies of scale
  - Availability of 2GHz allocation with multiple operators
- **Industry traction for 70/80 GHz**
  - Nokia, NTT DoCoMo, UCSD, NYU, EU Programs (miWaves, mmMagic)

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Why E-Band (70/80GHz)?

- A much anticipated solution to meet 4G data demand is network densification
  - 4G small cells will be deployed at street-level
  - Micro/pico base stations deployed on lamp posts and sides of buildings.
  - A pico base station will be deployed every city block and indoors.

- The E-Band system concept is intended to complement this small cell deployment
  - Availability of large contiguous bandwidth (1-2 GHz) can meet 5G requirements of 10 Gbps peak rate and 100 Mbps- 1Gbps Cell edge rates
    - Can be achieved with simple air-interface with 2x2 MIMO using Single Carrier, low PAPR waveform
  - Only band where the bandwidths are comparable to unlicensed band operation at 60GHz
  - Similar antenna and transceiver technologies to 60 GHz band can be used
  - Simultaneously provide backhaul for 4G and access/backhaul for 5G.

Nokia preparing for the 5G commercial network launches in 2020

Key milestones on the road to 5G

2014
- **DOCOMO Nokia 5G cooperation started**
- **Delivery of mmW trial system**
- Joint study of core networks for 2020 and beyond started

2015
- **5G HW/SW MWC demos**
- **Successful field tests for 5G mmW with NTT DOCOMO**
- Positive outcome for IMT and 5G at WRC2015

2016
- **5G system demo(s)**
- 5G standardization in 3GPP starting
- Successful delivery and field tests for 5G below 6GHz with NTT DOCOMO
- **Additional Features for 5G mmW**

2017
- **3GPP 5G work in full swing**
- Verification trials in Japan for basic technologies
- 5G Work in full swing in US

2018
- **Pre-standardized 5G trials in Japan for 5GMF Trial**
- WRC2019 preparation underway
- Phase 1 3GPP specifications completed
- Verification trials in Japan for radio & network

2019
- **Pre-commercial trials Rugby World Cup, Japan**
- Phase 2 3GPP 5G specifications completed
- WRC19 outcome clear with new bands for IMT

2020
- **1st commercial networks opening in Japan**
- 5G services experience during Tokyo Olympics
- Next phase on “5G” starts

*) 5G pipeline represents concepts, innovations and technologies that demonstrate possibilities (not commitments) for our future portfolio and roadmaps, not indicative of either timeline or order

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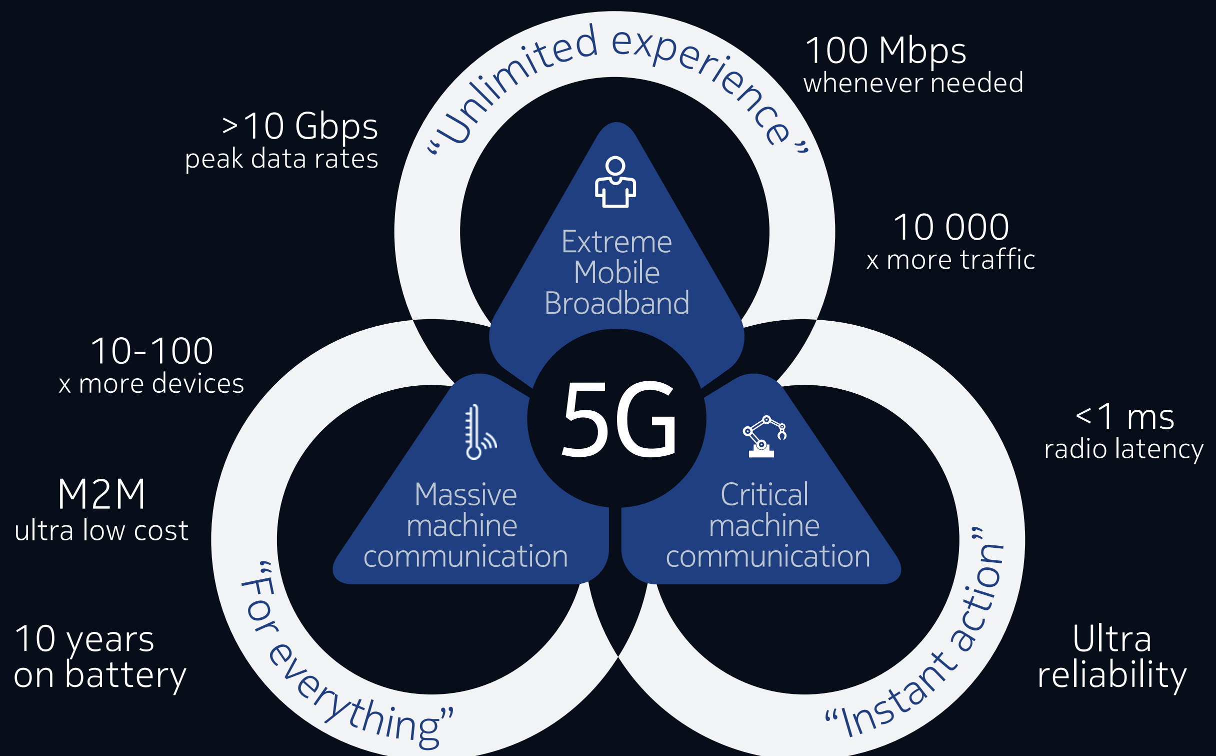
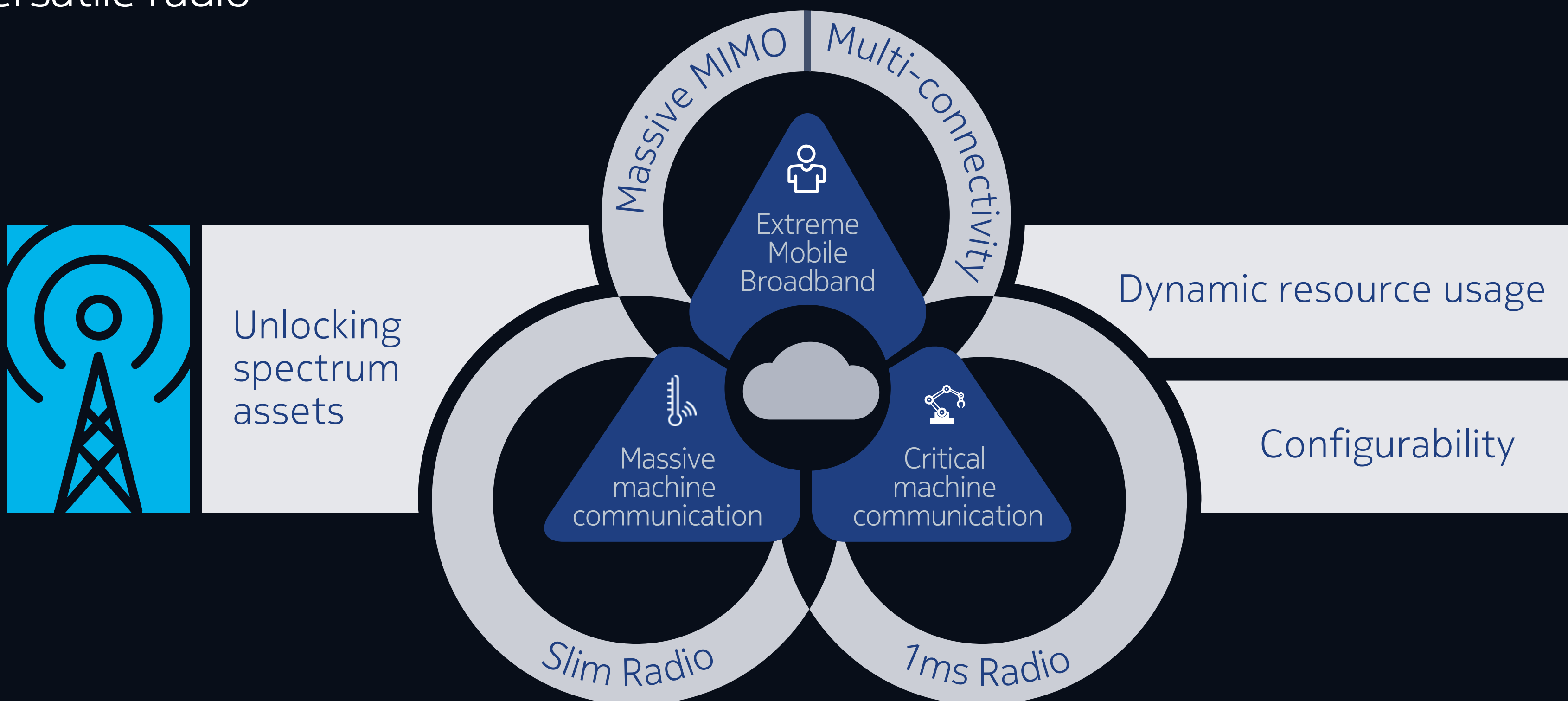
Requirements

Heterogeneous use cases – diverse requirements



5G for people and things | Key to the programmable world
Versatile radio



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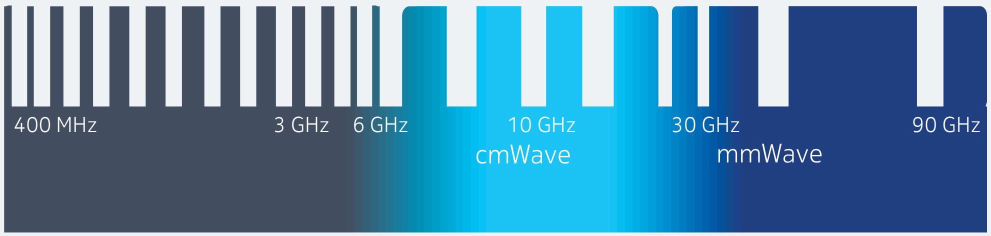
Unlocking new spectrum assets | The Foundation for 5G

Leveraging all bands, ranging from ~400MHz - 100GHz



Different characteristics, licensing, sharing and usage schemes

Carrier BW →n*20MHz — x * 100 MHz — 1-2GHz

Duplexing — FDD — TDD

Cell size: Macro, Small, Ultra Dense

Coverage ↔ Capacity

10,000 x | >10 Gbps | 100 Mbps | <1 ms | 10-100 x | ultra low | 10 years

Lower frequencies translate into continuous coverage for high mobility and reliability cases

Higher frequencies translate into higher capacity and massive throughput

Leading channel modeling know-how
Channel measurements from 3-73GHz

Leading METIS I & II spectrum work package

Worlds 1st,
Wide Are Single Frequency Network trial in UHF band

Worlds 1st
Licensed Shared Access demos/trial

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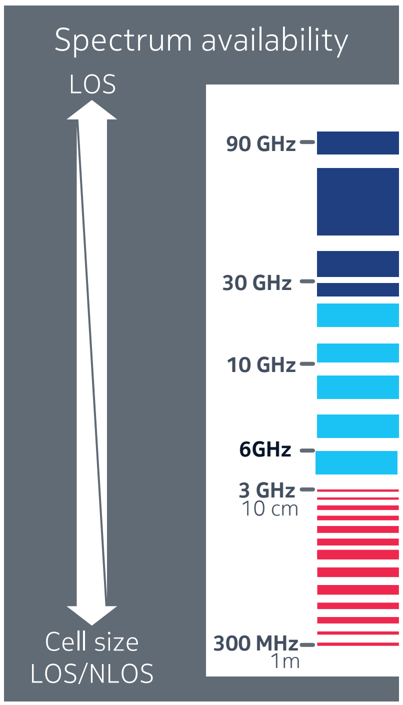
5G Scalable air interface design across frequency bands

Expanding the spectrum assets to deliver capacity and experience

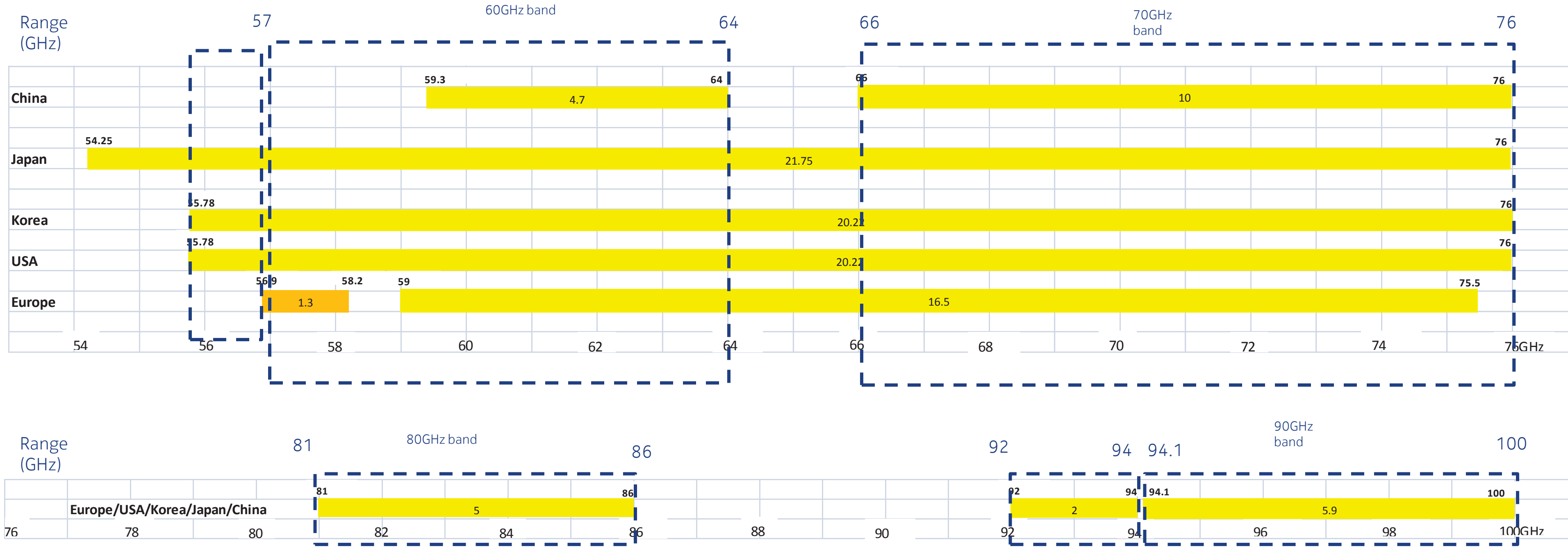


Spectrum	Antenna size	Network layer
~Nx1GHz carrier bandwidth Dynamic TDD	**Very small** Low rank MIMO and beamforming	Ultra high capacity and data rates
~Nx100 MHz carrier bandwidth Dynamic TDD	**Small** High Rank MIMO and beamforming	Boosting capacity and data rates
~Nx10 MHz carrier bandwidth FDD and TDD	**Medium - large** High Rank MIMO and beamforming	Providing base coverage and capacity

Overview of Spectrum at 54-100 GHz

Mapping Bands to 5G Requirements

54-100GHz, Co-Primary Mobile Allocation, min. 300MHz Contiguous Spectrum



Low rank MIMO for system BW in excess of 1 GHz with no interference management schemes

Low rank MIMO for system BW in excess of 1 GHz with no interference management schemes & Spectrum Sharing among operators

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Channel Measurements and Modeling

Why 6-100 GHz?

- 6-100 GHz expected to be in the scope of WRC 2019
- Channel models exist below 6 GHz
  - e.g., 3GPP 3D channel model, WINNER
  - Question: will these models be consistent with channel models from 6-100 GHz?
    - E.g., can a reasonable comparison be made between three simulated systems: one at 2.6 GHz, one at 10 GHz, and one at 72 GHz?
- Why 100 GHz as the upper limit?
  - Plenty of spectrum to exploit below 100 GHz, no need at this moment to go above 100 GHz
  - Technologically it is easier to stay below 100 GHz
  - Availability of measurements

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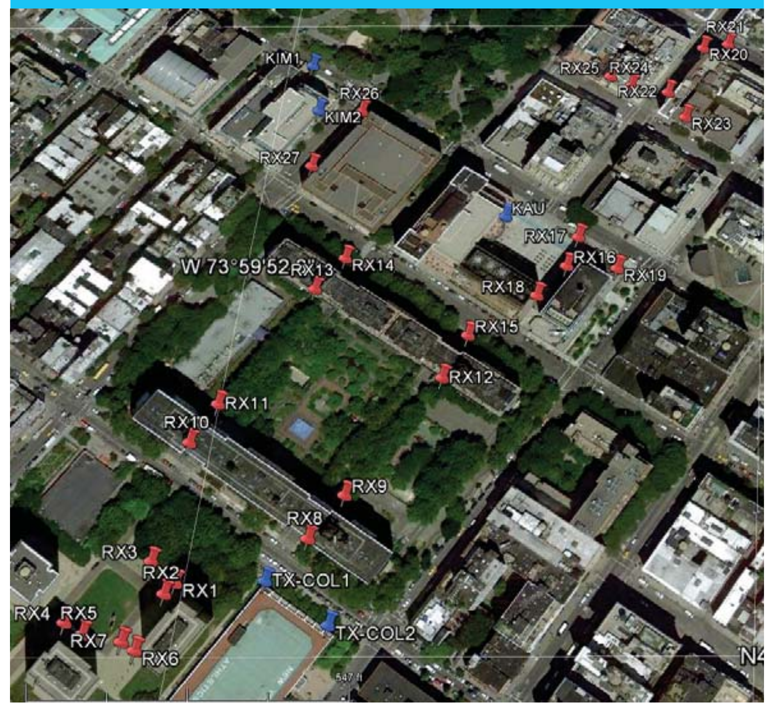
Preferred Channel Modeling Approach for 6-100 GHz

- Geometry-based stochastic ray-based channel model
  - Straight-forward model, captures dominant effects like clustering, delay/angle spreads, 3D nature of channel
- Path loss
  - Prefer statistical model for simplicity
  - Prefer FSPL (free-space path loss) reference-distance model
- Continuous channel model across 6-100 GHz
  - May need to initially develop model for different ranges (e.g., 3 frequency/band ranges, then see how to create a single model)
  - Shadow fading, Delay, Doppler, azimuth/elevation angular spread
  - Capture diffraction, reflection and scattering losses/effects
- Blockage models/propagation effects
  - E.g., buildings, people, trees, vehicles
  - Penetration loss, foliage loss, rain, oxygen (at least for 60 GHz, maybe 23 GHz)
  - Have model which does not require explicit dropping of buildings

73 GHz Measurements and Ray Tracing Studies

- **NYU Wireless**
  - Started in March 2013
  - Goal: characterize pathloss, polarization, delay spread, signal outage, penetration loss, angle spread at 73 GHz
- **Outdoor Measurements:** Manhattan (5 Tx, 27 Rx)
  - Backhaul-to-lamppost (17 or 7 m to 4 m)
  - Lamppost-to-mobile (17 or 7 m to 2 m)
  - Measurements taken with and without foliage
  - Measurements with narrow beam (7 degree) antennas at both Tx and Rx
  - Power-delay profiles collected for various azimuth/elevation angles
  - Some limited polarization measurement available
- **Ray tracing studies**
  - Used to fill in gaps from measurements to help develop channel models

Manhattan Measurement Setup



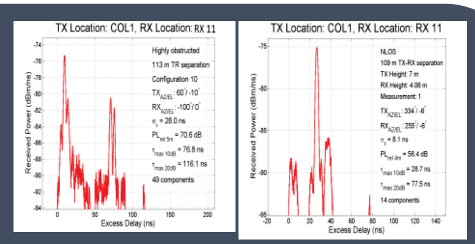
73 GHz Path Loss and System Range

mmWave network must be able to avoid, steer around, or adapt to obstacles

Omni directional path loss (1.0 m reference distance)

Channel measurements at 73 GHz
Cooperation with NYU and Aalto University

73 GHz	Backhaul-to-Backhaul		Base Station-to-Mobile	
	PLE	*SF (dB)*	*PLE*	*SF (dB)*
LOS	2.0	4.1	2.0	4.9
NLOS	3.5	7.9	3.3	7.6



Channel measurements at 28 GHz and 73GHz : NYU

	Uplink: 8x8-BS, 2x2-MS		Downlink: 4x4-BS, 4x4 MS	
	125 MB/s	10 GB/s	125 MB/s	10 GB/s
60 GHz	90.7 m	8.0 m	119 m	11.3 m
75 GHz	77.7 m	5.8 m	109 m	8.2 m
85 GHz	91.8 m	6.9 m	130 m	9.7 m
95 GHz	73.3 m	5.5 m	103 m	7.7 m

Outdoor measurements
Propagation channel is rich in multipath, both in terms of time delays and angular arrivals

2nd best path from 2-20 dB worse than dominant path

RMS delay ~125 nsec (omni antenna)

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NYU WIRELESS 73 GHz Indoor Measurements Overview

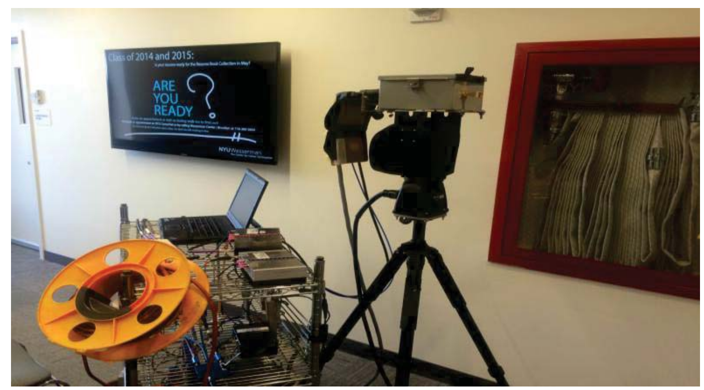
Measurements performed in a typical office environment

TX:
# of locations: 2
Height of antenna: 2.5 m

RX:
# of locations: 21
Height of antenna: 1.5 m

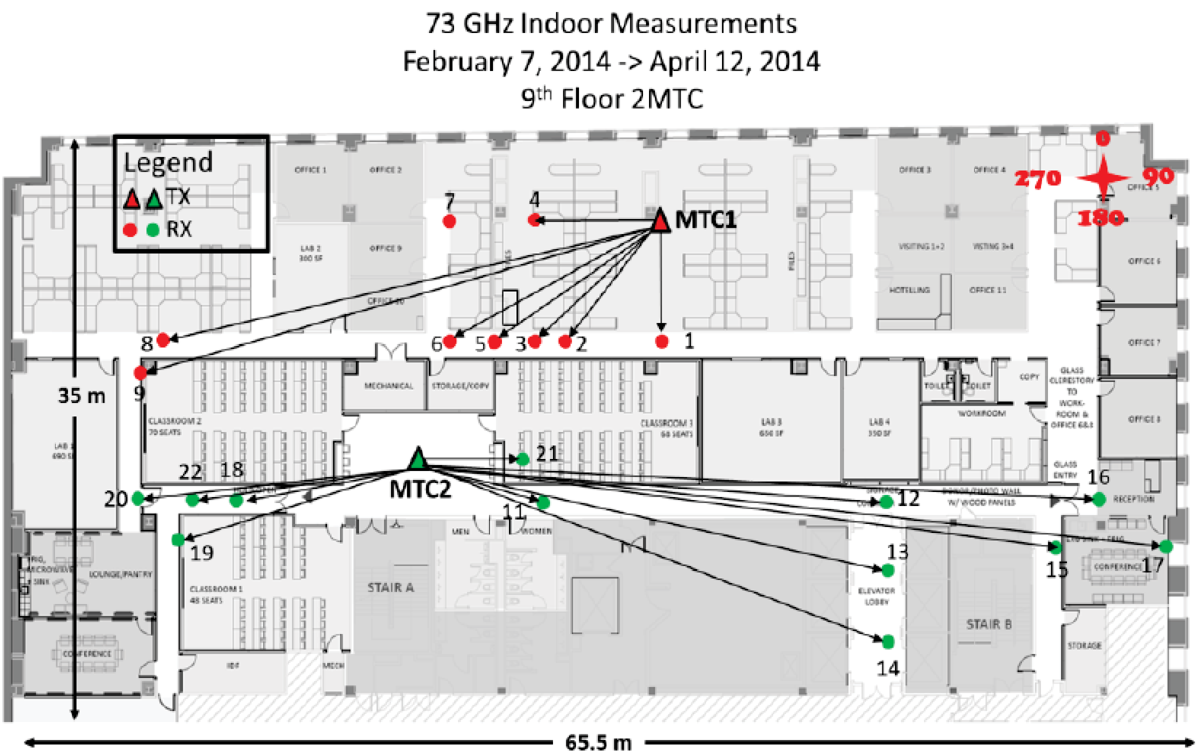
Directional antennas at both ends:
Boresight Gain: 20 dBi
HPBW: 15 degrees

Transmitter (TX)



Receiver (RX)

73 GHz Indoor Channel Measurements



Transmitter (TX)

Map of the indoor measurement office environment layout on the 9th floor of 2 MetroTech Center with transmitter locations represented as triangles and receiver locations represented as dots.

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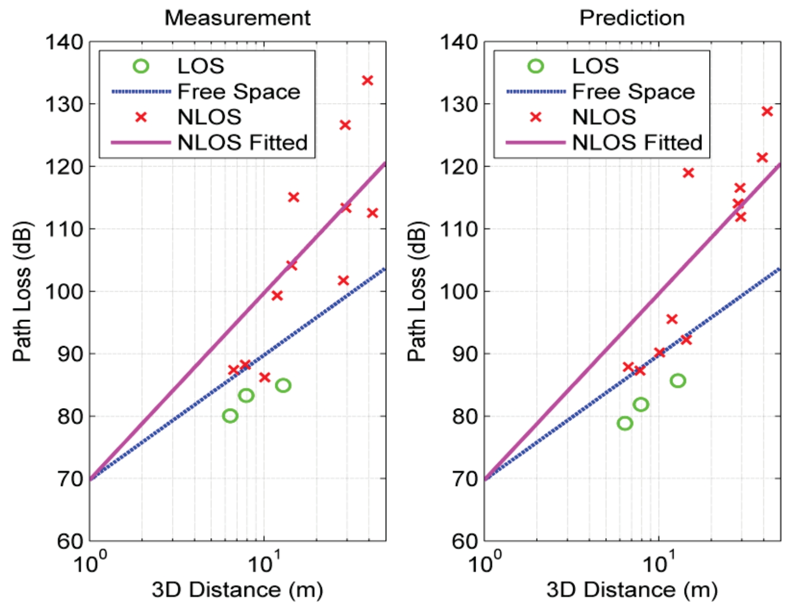
Comparison: Path Loss

$$LOS: PL = PL_0 + 10 \cdot 1.5 \cdot \log_{10}(d) + X_{\sigma,LOS} \; (d \geq 1m)$$
$$NLOS: PL = PL_0 + 10 \cdot 3.1 \cdot \log_{10}(d) + X_{\sigma,NLOS} \; (d \geq 1m)$$



Scenario	PLE	STD (dB)
LOS (measured)	1.5	1.01
LOS (predicted)	1.5	0.78
NLOS (measured)	3.1	8.90
NLOS (predicted)	3.1	8.54

Indoor Model vs. Outdoor Model at 73 GHz

Scenario		PLE	STD (dB)
Indoor	LOS (measured)	1.5	1.0
	LOS (predicted)	1.5	0.8
	NLOS (measured)	3.1	9.0
	NLOS (predicted)	3.1	8.5
Outdoor	LOS (B) (measured)	2.0	4.2
	NLOS (B) (measured)	3.5	7.9
	LOS (M) (measured)	2.0	5.2
	NLOS (M) (measured)	3.3	7.6

backhaul

access

Highlights:

1. Smaller RMS delay spread indoor vs. outdoor
2. Slightly larger azimuth angle spreads indoor vs. outdoor
3. Elevation angle spreads and biases monotonically decrease with distance
4. Azimuth angle distribution: uniform (compared to wrapped Gaussian for outdoor)
5. Full details in publications (VTC-Fall 2014 and ICNC 2015)

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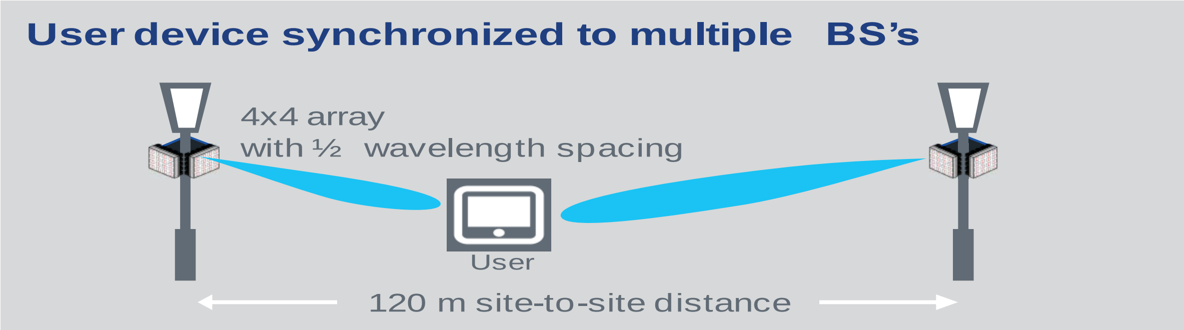
5G mmWave Experimental System

mmWave System Concept

- A much anticipated solution to meet 4G data demand is network densification
  - 4G small cells will be deployed at street-level
  - Micro/pico base stations deployed on lamp posts and sides of buildings.
  - A pico base station will be deployed every city block or roughly 120 meter site-to-site.
- The mmWave system concept is intended to complement this small cell deployment
  - Higher frequency cellular transceivers co-located with the 4G base stations.
  - Simultaneously provide backhaul for 4G and access/backhaul for 5G.



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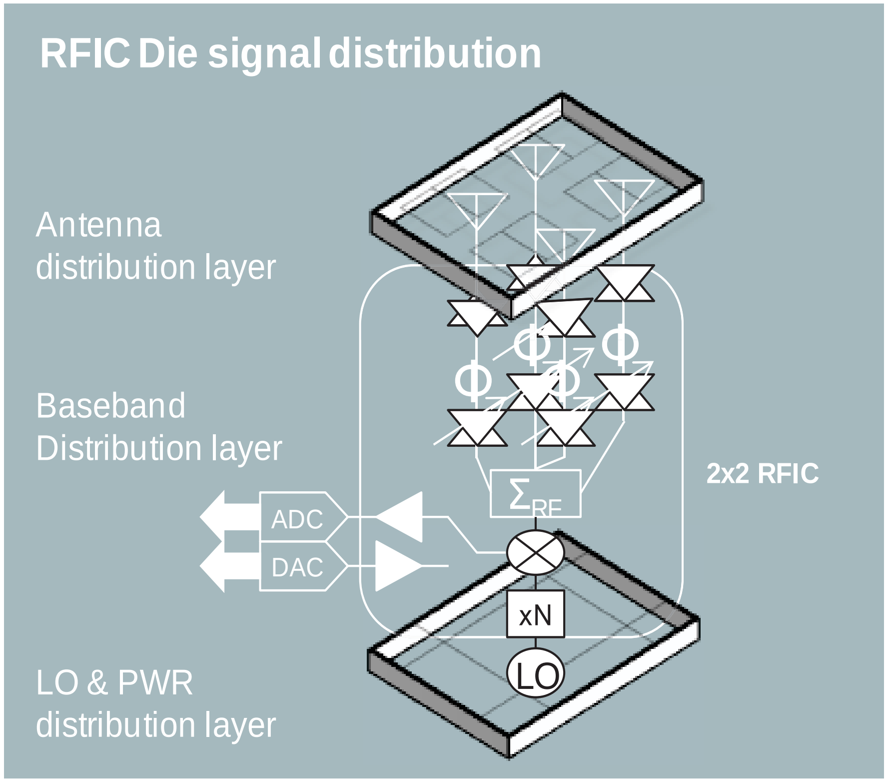
mmWave Massive MIMO/Beamforming Solution

- Power consumption is one critical aspect for mmWave deployments.
  - ADCs capable of sampling a 2 GHz BW signal will be a major factor in power consumption.
  - Full digital baseband transceiver behind each element would consume an unacceptable amount of power.
  - Analog (aka RF-radio frequency) beam forming techniques will be employed to steer the array elements on the panel.
- The antenna panel would host a highly integrated mmWave circuit
  - Array of patch antenna elements bonded to an antenna distribution layer with power amplifiers, low noise amplifiers and phase shifters.
  - Signal summed and down converted on the die and mixed down to where it could be generated or sampled by DAC and ADC
  - A separate antenna panel would be used for each orthogonal polarization.



5G mmWave Challenges & Proof Points

- Unique difficulties that a mmWave system must overcome
  - Narrow beamwidths, provided by these high dimension arrays
  - High penetration loss and diminished diffraction.
- Two of the main difficulties are:
  - Acquiring and tracking user devices within the coverage area of base station using a narrow beam antenna
  - Mitigating shadowing with Base station diversity and Rapidly Rerouting around obstacles when user device is shadowed by an opaque obstacle in its path.
- Other 5G aspects the current experimental system addresses:
  - High peak rates and cell edge rates (2.3 Gbps peak, 100 Mbps cell edge)
  - Low-latency (< 1ms)

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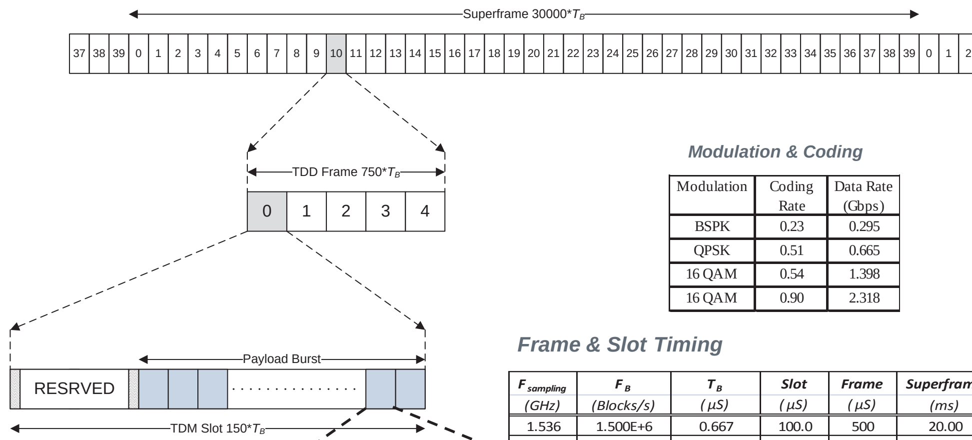
5G Experimental System Frame Structure

- Analog beamforming has implications for the modulation format used on the mmWave link
  - Beamforming weights are wide-band and, for OFDM, all subcarriers within a TTI must share the same beam
  - Time division multiplexing (TDM) is favored over frequency division multiplexing (FDM)
  - TDM suggests low PAPR modulation techniques can be considered to reduce the PA backoff and maximize the transmission power
- The mmWave link utilizes single carrier modulation to maintain a low. PAPR
  - PAPR is further reduced using $\pi/2$ shifting of BPSK, $\pi/4$ shifting of QPSK
- The QAM symbols are grouped into blocks of 512 symbols
- *The modulation format is called Null Cyclic Prefix Single Carrier (NCP-SC)[8]*
  - The QAM symbols are grouped into blocks of 512 symbols
  - M_{data} = 480 and M_{cp} = 32 provides 40 ns RMS delay spread resilience.
  - The null cyclic prefix can be increased or decreased on a per TTI basis without impacting the overall system numerology.
- The experimental system operates with a 1 GHz bandwidth using the 512 symbol NCP-SC block.
- A commercial system is envisioned to use a 1024 symbol NCP-SC block to achieve a 2 GHz bandwidth.
  - Achieves 10 Gbps peak rate with 2x2 MIMO



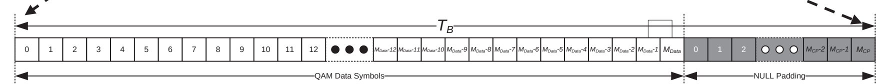
Modulation & Coding

Modulation	Coding Rate	Data Rate (Gbps)
BSPK	0.23	0.295
QPSK	0.51	0.665
16 QAM	0.54	1.398
16 QAM	0.90	2.318

Frame & Slot Timing

$F_{sampling}$ (GHz)	F_B (Blocks/s)	T_B (μS)	Slot (μS)	Frame (μS)	Superframe (ms)
1.536	1.500E+6	0.667	100.0	500	20.00
1.500	1.465E+6	0.683	102.4	512	20.48

NCP-SC Block



NCP-SC Numerology

Block Format	M_{Data}	M_{CP}
A	480	32
B	960	64

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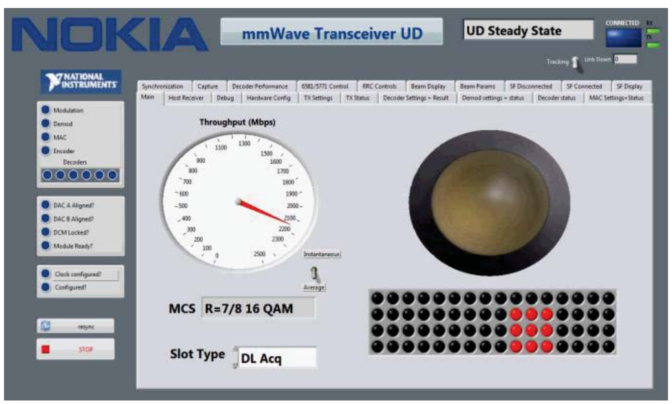
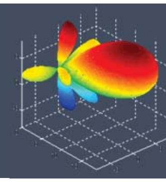
Nokia 5G mmWave beam tracking demonstrator



Lens antenna with 64-beam switching

3˚ beam width



70 GHz band
1 GHz bandwidth

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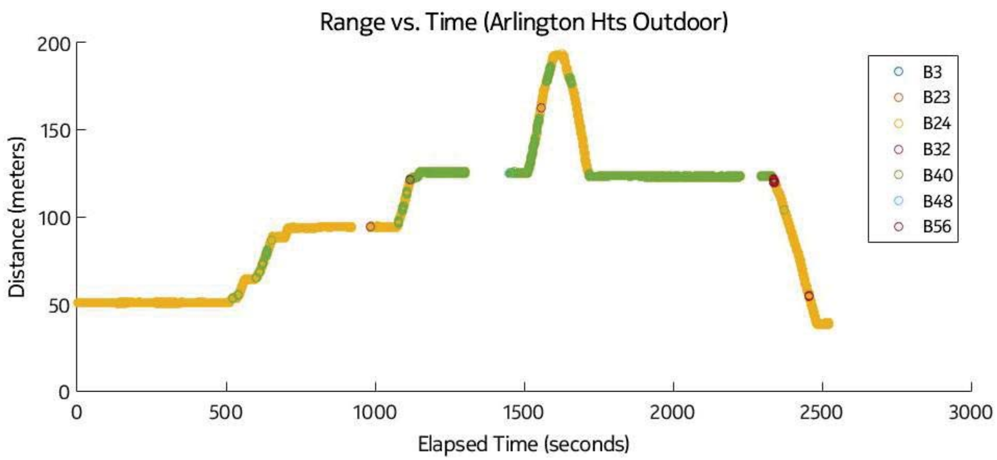
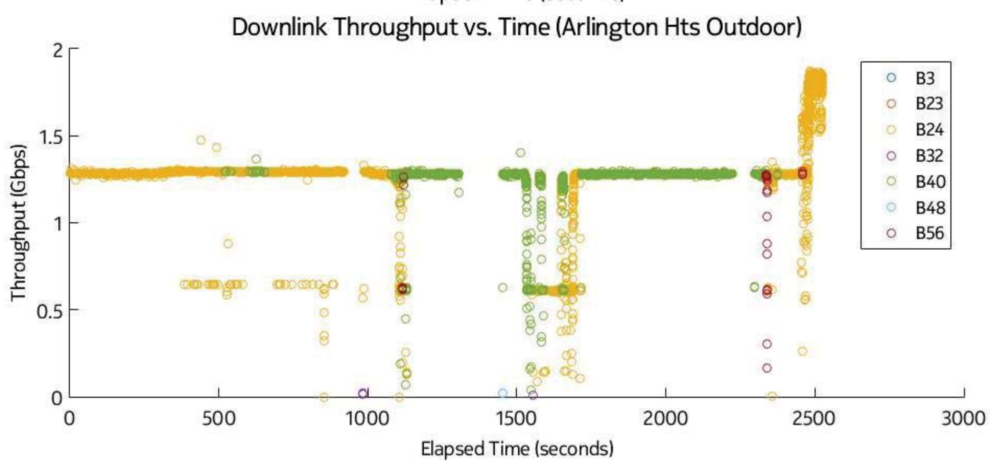
5G mmWave Outdoor results @ AH campus





Parameters	Value
Operating Frequency	73 GHz
Bandwidth	1 GHz
Modulation	Null Cyclic-Prefix Single Carrier 16 QAM Single Stream (SISO)
Antenna Beamwidth	3 degrees
Antenna Steering Range	34 degrees Azimuth 8 degrees Elevation

Outdoor Experiments @ 73 GHz very promising

Maximum Range of 200meters

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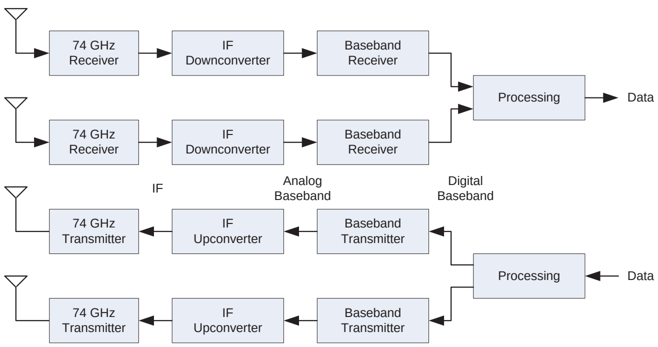
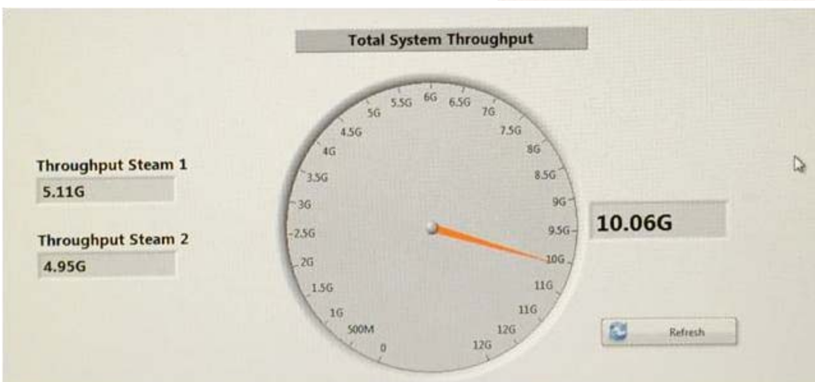
Play Video....

mmWave PoC System @ 2GHz BW supporting 10 Gbps Peak rate

New platform designed by NI to meet Nokia's 5G specification





Parameters	Value
Operating Frequency	~74 GHz
Bandwidth	2 GHz
Peak Rate	~10 Gbps
Modulation	Null Cyclic-Prefix Single Carrier R=0.9, 16 QAM 2x2 MIMO
Antenna	Horn Antenna

10 Gbps peak rate using a prototype of NI's mmWave platform- demonstrated at 5G Brooklyn summit

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Summary

- Experimental systems are critical to proving that higher frequencies can be used to achieve 5G objectives.
- The 73.5 GHz, 1 GHz BW experimental system with a steerable 28 dB gain, 3 degree HPBW antenna can help prove many of the 5G concepts.
- Initial work on a single link system demonstrates the feasibility of acquiring and tracking user devices within the coverage area of base station using a narrow beam antenna
- 10 Gbps Peak Rate can be achieved using 2 GHz BW, 16 QAM and 2x2 MIMO
- Future work will include a multi link system will demonstrate how shadowing can be mitigated with base station diversity and rapidly rerouting around obstacles

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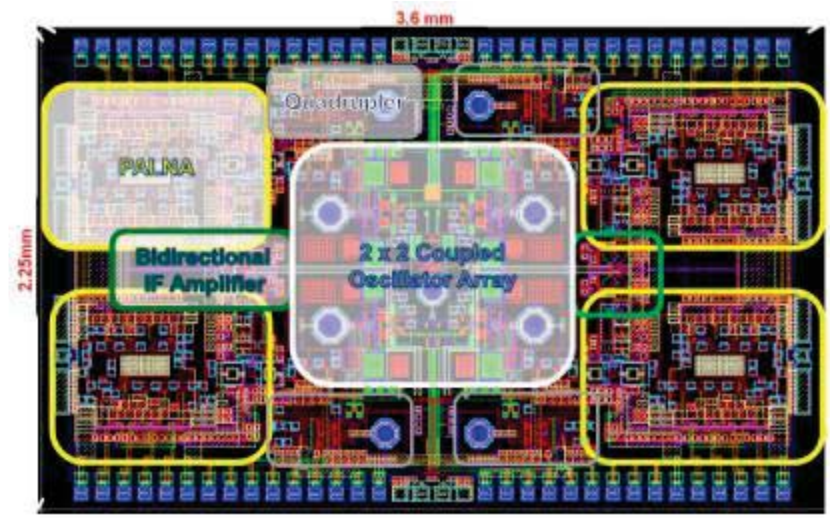
mmWave RFIC Research with Universities

Phased Array Research

University Partnerships – UCSD 2x2 ESA MMIC

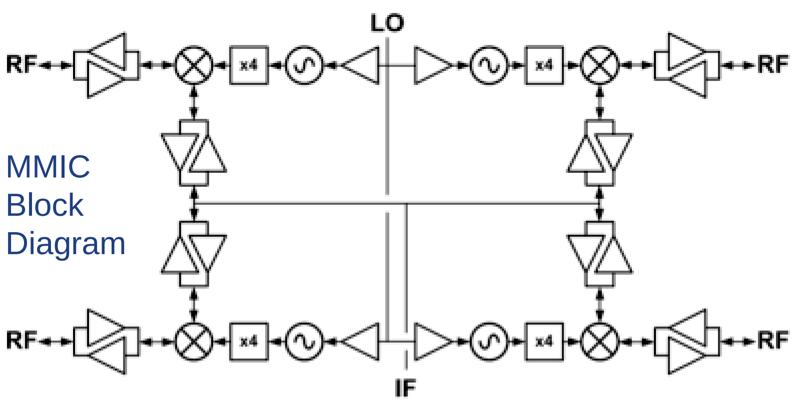
Electrically Steered Array (ESA) High Level Features

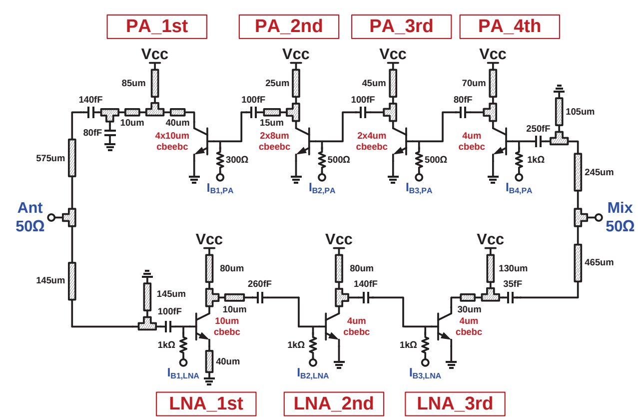
- 4 Tx/Rx chains
  - Wideband 71GHz and 87GHz, IF bandwidth > 2GHz
  - Transmitter power >= 10dBm linear Pout.
  - Receiver noise figure < 10dB
  - Bidirectional up/down converter mixer+IF and PA/LNA
  - RF ports arranged to support a 2x2 2-dimensional array
- Single IF port with IF up/down combining network for the 4 Tx/Rx chains
- Phase steering via tuned VCO injection locking with external LO port
  - Enables LO distribution between MMICs for scalable arrays
- IBM 9HP SiGe Semiconductor Process
  - State of the art and restricted access at time of design



2x2 ESA Layout

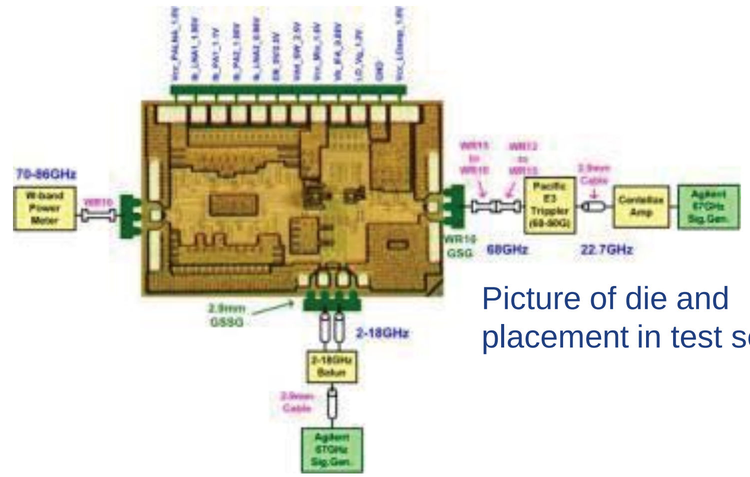
MMIC Block Diagram





Bidirectional PA/LNA Schematic

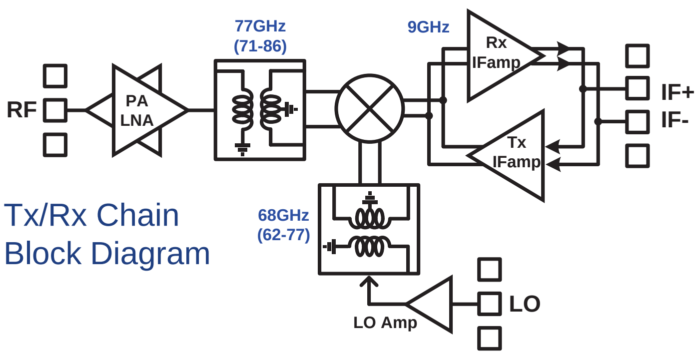
Phased Array Research
UCSD 2x2 ESA MMIC – PA/LNA Test Die



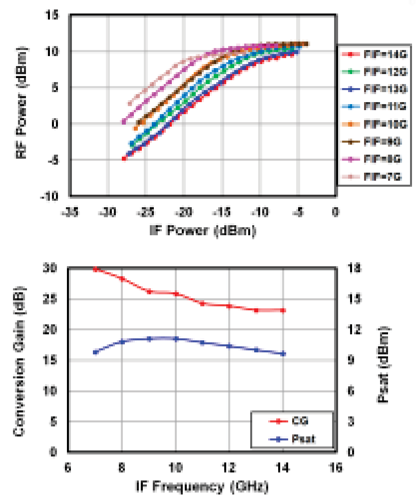
Picture of die and placement in test setup

Test Die for Bidirectional PA/LNA, Mixer, IF Amp

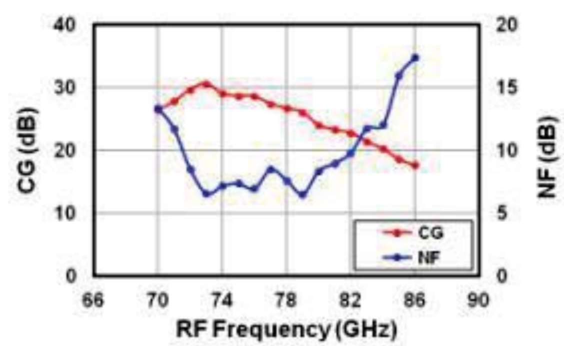
- Enables more isolated testing of Tx & Rx RF chain
- All elements fully functional
  - Pout meets requirement
  - Conversion gain slightly low but acceptable
  - NF slightly high
  - Frequency response somewhat narrower than sim but still WB
- With new semiconductor process, i.e. IBM 9HP, it's typical for the design library to require some tuneup and expect variance in actual performance



Tx/Rx Chain Block Diagram



Tx Pout and Conv. Gain



Rx NF and Conv. Gain

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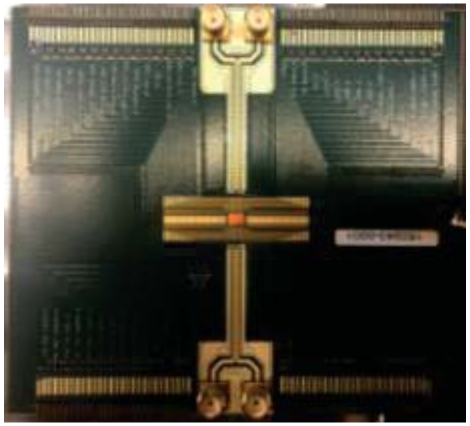
Phased Array Research

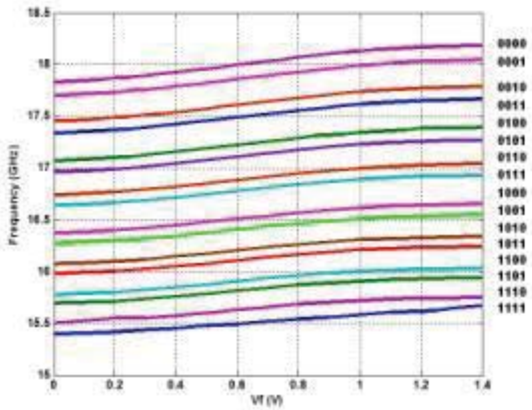
UCSD 2x2 ESA MMIC Testing

Picture of test board with ESA MMIC



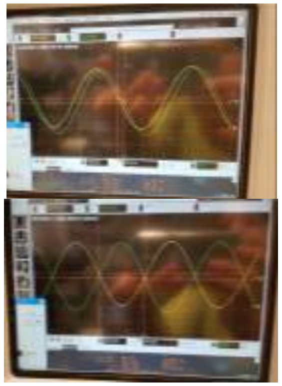
Testing of the 2x2 ESA MMIC

- All Tx/Rx elements fully functional
    - PA/LNA, mixer & IF amp already tested on PA/LNA test die
- Key areas to characterize on this die are:
    - VCO tuning range
        - Via switched capacitor (large step) & varactor (fine step)
    - LO injection locking between external LO and internal VCOs
    - Phase delay via tuning of VCOs
- All LO injection locking elements and features are fully functional!
    - In process of completing single chain performance
    - Initial results appear to be within ~10% of simulation
    - Next step will be to do conducted phase steering measurements between T/R chains

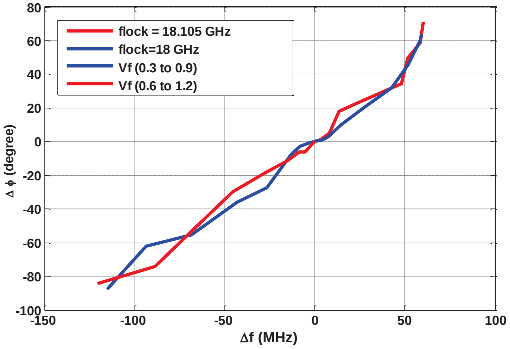


VCO tuning

- Each line is course setting via switched capacitor under digital control
- Fine freq control via voltage control of a varactor
- >16% tuning range
- Freq x4 for final LO to mixer



Delay/phase shift of 15 ps and 106 ps



Phase shift range. Note: 4x final phase shift after x4 multipliers.

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List of Papers and Press Releases

Summary of Press Releases

- **Nokia and NYU Press Release-** http://networks.nokia.com/news-events/press-room/press-releases/nokia-and-ntt-docomo-pave-the-way-for-5g
- http://engineering.nyu.edu/press-release/2015/04/08/nokia-networks-nyu-wireless-host-brooklyn-5g-summit-advance-super-fast-gene
- **CNNMoney** – This is the Fastest Cell Phone Network Ever (ABC7, Grant Daily, WAPI, Magic 107.3, NASH, WSEE, C4K, KSPR, WYFF, WDSU)
- **Converge!** – Nokia Networks Hits 10Gbps Over the Air at 73 GHz
- **EE Times** – Nokia Demos 10 Gbits on High Frequency
- **FierceWirelessTech** – Nokia Networks Paves Way for 5G with 10 Gbps Demo at Brooklyn 5G Summit
- **IP Carrier** – Will Mobile be a Full Substitute for Fixed Internet Access in 10 Years?
- **MoneyTalksNews** – Fastest Cell Network Ever Almost Here (Yahoo! Finance)
- **NewsMax** – Nokia's 5G Tech Too Fast for Current Cellphones to Handle
- **PCC Mobile Broadband** – Nokia Networks, NI Demo 10Gbps at the Brooklyn 5G Summit
- **RCRWireless** – 10 Gbps Wireless Speeds Demoed by Nokia and National Instruments
- **StreetWise** – Nokia Corporation; Test 5G Speed 10Gbps Future Capabilities
- **Technical.ly Brooklyn** – 3 prototypes that could be cornerstones of our wireless future
- **Technical.ly Brooklyn** – Wireless industry reaches consensus on 5G goals
- **WirelessWeek** – First News Briefs: Aerialink, Nokia, NI, Samsung, Broadpeak

Nokia Papers on mmWave Concept

1. M. Cudak, A. Ghosh, T. Kovarik, R. Ratasuk, T. Thomas, F. Vook, P. Moorut, "Moving Towards mmWave-Based Beyond-4G (B-4G) Technology," in *Proc. IEEE VTC-Spring 2013*, June 2-5, 2013.
2. S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, A. Ghosh, "Millimeter Wave Beamforming for Wireless Backhaul and Access in Small Cell Networks," IEEE Transactions on Communications, vol. 61, No. 10, October 2013.
3. S. G. Larew, T. A. Thomas, M. Cudak, A. Ghosh, "Air Interface Design and Ray Tracing Study for 5G Millimeter Wave Communications," in Proc. IEEE Globecom 2013, Atlanta, USA, 9-13 December, 2013
4. Anup Talukdar, Mark Cudak, Amitava Ghosh, "Handoff Rates for Millimeterwave 5G Systems," submitted IEEE VTC Spring 2014, Seoul, Korea
5. T. A. Thomas, H. C. Nguyen, G. R. MacCartney Jr., T. S. Rappaport, "3D mmWave Channel Model Proposal," *submitted to IEEE VTC-Fall 2014*.
6. A. Ghosh, T. A. Thomas, M. Cudak, R. Ratasuk, P. Moorut, F. Vook, T. S. Rappaport, G. R. MacCartney Jr., S. Sun, "Millimeter Wave Enhanced Local Area Systems: A High Data Rate Approach for Future Wireless Networks," submitted to IEEE Journal on Selected Areas in Communications 2014
7. T. A. Thomas, F. W. Vook, "Method for Obtaining Full Channel State Information for RF Beamforming," IEEE Globecom 2014.
8. T. A. Thomas, F. W. Vook, "System Level Modeling and Performance of an Outdoor mmWave Local Area Access System," submitted to PIMRC 2014.
9. F. W. Vook, A. Ghosh, T. A. Thomas, "MIMO and Beamforming Solutions for 5G Technology," IMS 2014, June 2014.
10. H. C. Nguyen, G. R. MacCartney Jr., T. Thomas, T. S. Rappaport, B. Vejlgaard, P. Mogensen, "Evaluation of Empirical Ray-Tracing Model for an Urban Outdoor Scenario at 73 GHz E-Band," submitted to VTC-Fall 2014.
11. J. Song, S. G. Larew, D. J. Love, T. A. Thomas, A. Ghosh, "Millimeter Wave Beam-Alignment for Dual-Polarized Outdoor MIMO Systems," in Proc. Globecom 2013 Workshop on Broadband Wireless Access, December 2013.
12. F. W. Vook, T. A. Thomas, E. Visotsky, "Massive MIMO for mmWave Systems", Asilomar Conference November 2014
13. M. Cudak, et al., "Experimental mmWave 5G cellular system," Proc. Globecom 2014, Workshop on Mobile Communications in Higher Frequency Bands, December 2014.

